

# Radial mixing in the outer Milky Way disk caused by an orbiting satellite

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## ABSTRACT

Using test particle simulations we examine the structure of the outer Galactic disk as it is perturbed by a satellite in a tight eccentric orbit about the Galaxy. A satellite of mass a few times  $10^9 M_\odot$  can heat the outer Galactic disk, excite spiral structure and a warp and induce streams in the velocity distribution. We examine particle eccentricity versus the change in mean radius between initial and current orbits. Correlations between these quantities are reduced after a few satellite pericenter passages. Stars born in the outer galaxy can be moved in radius from their birth positions and be placed in low eccentricity orbits inside their birth radii. We propose that mergers and perturbations from satellite galaxies and subhalos can induce radial mixing in the stellar metallicity distribution.

## 1 INTRODUCTION

There is evidence for past and ongoing accretion of small objects by the Milky Way, the most dramatic one being the disrupted Sgr dwarf galaxy (Ibata et al. 1994). The outer disk of the Galaxy may be constantly perturbed by small satellites or structure in the galactic halo which can contribute to the stellar halo population (Helmi 2008). Perturbations from satellite galaxies or merging subhalos with mass of order  $10^{10} M_\odot$  can cause ring-like structures in the Galactic plane (Tutukov & Fedorova 2006; Younger et al. 2008; Kazantzidis et al. 2008) similar to the Monoceros stellar stream (Newberg et al. 2002; Juric et al. 2008). Cosmological simulations suggest that such events are not uncommon. Our galaxy could have experienced pericenter crossings within 20kpc of the Galactic center with about 6 separate subhalos of this size since a redshift of 1 (Kazantzidis et al. 2008) (also see Purcell et al. 2007, 2009). Mergers and orbiting satellite subhalos can induce a warp, thicken the Galactic disk and leave behind stellar streams (Bekki & Freeman 2003; Helmi et al. 2003; Meza et al. 2005; Peanrrubia et al. 2005; Purcell et al. 2007; Hopkins et al. 2008; Kazantzidis et al. 2008; Villalobos & Helmi 2008; Purcell et al. 2009).

The metallicities of stars in the solar neighborhood exhibit a large scatter that is not strongly dependent on their age or orbital eccentricity (Edvardsson et al. 1993; Haywood 2008). The lack of strong correlations in these properties can be explained if stars migrate radially from their birthplace (Haywood 2008; Schoenrich & Binney 2009). Radial migration can be caused by resonances associated with transient spiral structure (Sellwood & Binney 2001; Roskar et al. 2008). Here we explore the possibility that ra-

dial migration can be induced tidally by an orbiting satellite galaxy.

## 2 TEST PARTICLE SIMULATIONS

The numerical simulations integrate test particle trajectories in a gravitational potential in cylindrical coordinates with a flat rotation curve

$$\Phi(r, z) = \frac{v_c^2}{2} \log(r^2 + z^2/q^2 + a^2) \quad (1)$$

where  $q < 1$  corresponds to an oblate system and  $a$  is a smoothing length or core radius. Disk particles are initially chosen with radial distribution  $n(r) \propto r^{-1}$ . Azimuthal and epicyclic angles are randomly chosen. Particle eccentricities and inclinations are initially chosen from a Rayleigh distribution so as to create a Gaussian distribution in both radial and vertical velocities.

A single massive particle is placed at apocenter to mimic the effect of the dwarf satellite and integrated in the same potential as the disk particles. The disk particles feel the perturbations from the dwarf galaxy, though not each other. The dwarf galaxy is put on an orbit with eccentricity and orbital period similar to those used to predict the location and motions of the Sgr dwarf debris (Johnston et al. 1999; Law et al. 2005). We chose an orbit for the dwarf galaxy similar to that of Sgr dwarf because this orbit is well constrained by observations and because its pericenter is small enough that a more massive dwarf galaxy in this orbit would have strongly perturbed the Milky Way disk. The force from the satellite is softened at short distances so that spurious large velocities are not induced when it passes through the

Galactic disk. The test particles are integrated for four radial oscillations periods of the dwarf galaxy orbit. Thus the disk feels four close pericenter passages. The gravitational potential of the Galaxy is not varied during the simulation, thus there is no indirect perturbation that should have been caused by variation in the position of the center of the galaxy with respect to the center of mass frame. As these are test particle simulations, the self-gravity of the disk and response of the halo to the satellite are neglected.

We work in units of the Sun’s radius from the Galactic center ( $R_0 \approx 8.5$  kpc) and the rotational velocity for a particle in a circular orbit at  $R_0$  or  $v_0 \approx 220$  km/s. Masses are given in units of  $M_0 = \frac{v_0^2 R_0}{G} \approx 10^{11} M_\odot$ . Timescales are given in units of the rotation period at  $R_0$  or  $P_0 \approx 240$  Myr. Initial disk particles are chosen between  $0.5$  and  $2.5 R_0$ . The softening length for the satellite is  $0.1 R_0$  and that for the rotation curve is  $a = 0.1 R_0$  and within the radii of disk particles simulated. The simulations are run with code described by Bagley et al. (2009) but lacking a bar perturbation. To compute spatial distributions, we used  $10^5$  particles. To compute mean velocity components, mean disk height and angular momentum and energy distributions we used simulations with  $10^6$  particles. We used simulations of  $10^7$  disk particles to compute velocity distributions of stars in the neighborhood of a point in the disk. This allows us to search for fine structure in the velocity distribution of stars near a specific location in the disk (like the solar neighborhood).

While the current mass of Sgr dwarf galaxy  $\sim 5 \times 10^8 M_\odot$  is not massive enough to strongly perturb the Galactic disk, this galaxy could have been a few times  $10^9 M_\odot$  in the past (e.g., see discussion by Law et al. 2005; Zhao 2004) and so similar in mass to the subhalos considered by Kazantzidis et al. (2008). In the context of a CDM hierarchical galaxy formation paradigm, Kazantzidis et al. (2008) show that it is not uncommon for a subhalos of sizescale  $\sim 10^{10} M_\odot$  to merge with a Milky Way sized galaxy. We consider satellites on tight orbits with pericenters approximately  $1.3 R_0$  and masses  $0.03$  to  $0.1 M_0$  ( $3$  to  $10 \times 10^9 M_\odot$ ). Our satellites have pericenter and period similar to the shorter values estimated for Sgr galaxy. In our units the estimated peri and apocenter Galactocentric radii of Sgr galaxy’s orbit are  $1.3$ – $2.0$  and  $6.5$ – $7.0$  (Law et al. 2005). Our simulation parameters are listed in Table 1. The galaxy halo potential is chosen to be mildly oblate with  $q = 0.95$ . We chose a non-spherical potential so as to allow mild variations between pericenter galactocentric radii. Variations in the orbit would have been present if dynamical friction were present or if the Milky Way gravitational potential were allowed to respond to the perturbation.

## 2.1 Morphology

In Figure 1a we show the morphology in the plane of the Galaxy as a function of time from the simulation A1 with parameters listed in Table 1 and satellite on a polar orbit. Images are shown separated in time by  $3/4$  of  $P_0$ , the orbital period at the Sun. In Figure 1 the galaxy is oriented so that rotation is clockwise.

The simulation shown in Figure 1a has satellite orbit resembling that of Sgr dwarf. The orbit is oriented so that is it polar or lying in the  $y, z$  plane. The first pericenter

passage is experienced  $1.5$  orbital periods (at the Sun) from the beginning of the simulation. The first pericenter occurs below the Galactic plane. The second and third pericenter passages occur closer to the Galactic plane. The pericenters close approaches and passages through the plane of the Galaxy induce velocity impulses in the stars in Galactic disk. Following the second pericenter spiral structure is induced in the disk with structure similar to that seen in simulations of flybys (Tutukov & Fedorova 2006; Younger et al. 2008). The disk also exhibits some lopsidedness though not as much as displayed by the atomic hydrogen distribution in the Milky Way’s outer disk (Levine et al. 2006a).

Multiple close passages cause stronger spiral structure than a single flyby. This is not surprising as the tidal force during pericenter lasts longer when the orbit is bound rather than parabolic, and the disk cannot completely dynamically relax between pericenters. The disk receives multiple perturbations from each close approach which can add constructively or destructively to particle eccentricity or inclination as the timescale between pericenters, about  $3 P_0$ , is comparable to the orbital period at  $2 R_0$  (or  $2 P_0$ ).

Inspection of Figure 1 shows that particle orbits can intersect other orbits. Stellar orbits can cross each other but gas clouds would collide. As we see orbits that intersect each other, the gas distribution may differ from the stellar distribution. It is interesting to place this in perspective with the outer Galaxy. There is no clear structure in the HI distribution (as seen in the maps by Levine et al. 2006a) in the Milky Way associated with the Monoceros stream (as seen in the maps by Juric et al. 2008) even though there is HI gas detected in the same region.

Figure 1b is similar to Figure 1a except showing a the disk perturbed by a satellite on a prograde inclined orbit (simulation A2). The orbit’s spin axis is  $30^\circ$  from the Galactic pole. We see that the perturbations on the disk are stronger for the inclined orbit. The outer disk is more strongly scattered and the induced spiral structure is stronger.

After the last pericenter passage, the mean height of the disk above the Galactic plane, radial and tangential velocity components (in Galactocentric coordinates) are shown in Figure 2 for both simulations. For these plots the radial velocity component is positive in the direction away from the Galactic center. The velocity of a particle in a circular orbit has been subtracted from the tangential velocity component.

As have other works (e.g., Tutukov & Fedorova 2006; Younger et al. 2008; Kazantzidis et al. 2008) we find that the satellite induces spiral structure in the outer disk that is similar to that in Monoceros stream. The tangential velocity component is not expected to be high (second panels from top in Figure 2) but there should be moderate radial velocity variations (top panels in Figure 2). A comparison between the mean velocity components, the density distribution and the mean height (shown in the second panels from bottom in Figure 2) suggests that there could be correlations between these quantities in the outer Milky Way, though as we have neglected self-gravity in the disk, we should be cautious with this implication.

We see from the second panel from the bottom in Figure 2 that a warp has been excited by the passages of the satellite. The warp is complex and not well described by a single Fourier component as is true for the outer Milky

Way (Levine et al. 2006b). However, its amplitude for the polar orbit simulation is smaller than that observed in the outer Milky Way even though the satellite,  $6 \times 10^9 M_\odot$  exceeds that estimated for the Sgr dwarf galaxy by a factor of 10. The outer Milky Way extends out of the plane 4-6 kpc which would be  $z \sim 0.5$  in units of  $R_0$ . From Figure 2 we see that the mean height reaches only  $z \sim 0.2$ . A similar mass satellite on a tight orbit but inclined to the disk does induce a warp large enough to account for features seen in the outer galaxy (as shown in Figure 2b). There is currently no evidence for a coherent satellite with mass as large as we are simulating that could account for the morphology of the outer galaxy. As explored by Weinberg (1998); Weinberg & Blitz (2006) with the LMC resonant perturbations could be important and a self-gravitating disk would be needed to more accurately simulate the coupling, or the response of the Milky Way halo is important and a live halo would be needed to simulate the effect. Alternatively objects as massive as simulated here, possibly merging with the outer Galaxy, are needed to explain the Galactic warp.

## 2.2 Velocity distribution at a single position

We consider whether the perturbations caused by the satellite would cause structure in the velocity distribution in a particular location such as the solar neighborhood. Figure 3 shows the velocity distribution computed in a region centered at the solar position from stars that are within a distance of  $0.05R_0$  or  $\sim 400$  pc. We find that spiral arms induced by the satellite can increase stellar eccentricities sufficiently that streams can be seen in the velocity distribution. Large velocity streams are not well populated but streams at about 40 km/s (at  $u$  or  $v \approx \pm 0.2$  from the local standard of rest in units of  $V_0$ ) are seen in the simulations, particularly at positive  $v$ . Stars at positive  $v$  correspond to those from the outer galaxy with eccentricity high enough that they can be seen in the solar neighborhood. These stars would correspond to a disk population that has lower metallicity than the thin disk population present in the solar neighborhood because they were born in the outer galaxy. Such a population with origin in the outer disk has been postulated by Haywood (2008).

Small population streams of stars at high velocity in the solar neighborhood have primarily been interpreted as remnants from disrupted satellites (e.g., Navarro et al. 2004; Helmi et al. 2006). Here we find that they could also be comprised of disk stars but associated with recent tidal perturbations to the disk caused by moderate mass satellites or mergers.

The relaxation or shearing timescale (in rotation periods) for epicyclic motions is fairly short. After perturbations cease, structure in the velocity distribution will become less and less prominent. Minchev et al. (2009) shows that streams could last a few Gyrs but would get closer and closer together at later times. In our simulations 1 Gyr corresponds approximately to 4 orbital periods. In our simulations because perturbations recur, the disk would never be relaxed and multiple streams would always be present. If the satellite were allowed to decay via dynamical friction, be disrupted and merge with the Galaxy then we expect that the streams would become closer together finally dissolving into a diffuse distribution a few Gyrs afterward the merger.

## 2.3 Angular momentum and eccentricity changes

After the satellite has disrupted or merged with the Galaxy we expect spiral structure induced in the disk will wind up in 5-10 rotation periods. Compact stellar streams such as seen in Figure 3 will wrap into a diffuse smooth distribution via dynamical relaxation (e.g., Minchev et al. 2009). However stars excited to higher eccentricities are likely to remain at higher eccentricity. We now look at angular momentum and eccentricity changes in the disk induced by the satellite.

For 3 different ranges of initial radii and at different times we compute  $dL$ , the angular momentum change and  $e$ , the particle eccentricity. The angular momentum change is computed by subtracting the current one from the initial one. The eccentricity is estimated as  $e \sim \sqrt{(u^2 + 2v^2)/2}$  appropriate for a flat rotation curve (Arifanto & Fuchs 2006).

In Figure 4 shows eccentricity,  $e$ , versus angular momentum change,  $dL$ , at the times separated by  $2 P_0$  for simulations A1 and A2. Each row is computed for a different range of initial radii. The top row corresponds to initial radius in the range 1.3 – 1.5, the middle row 1.0 – 1.3 and the bottom row 0.8 – 1.0. The left hand panels show the  $e$  versus  $dL$  distribution following only a single pericenter passages. At this time little heating has taken place and there are strong correlations between angular momentum change and particle eccentricity caused by the satellite. However after 3 more pericenter passages the correlations between these properties are much weaker. From the top-right panels, particularly in Figure 4b for the inclined satellite orbit, we can see that stars in the outer disk can experience changes in their angular momentum but also be placed in low eccentricity orbits. This means that a particle in a circular orbit can be moved to a nearly circular orbit with a different radius. This change can be called radial migration though here it is caused by gravitational scattering.

Stars with negative  $dL$  have orbits with mean radii interior to their initial radius whereas stars with positive  $dL$  have mean radii outside their initial radii. We see from Figure 4b that a significant population of stars from the outer galaxy that crosses into the inner galaxy. This implies that perturbations from satellites or subhalos can cause stars from the outer disk to reach the solar neighborhood. This mechanism provides a possible explanation for the population of moderate metallicity disk stars with positive  $v$  velocity components originating in the outer galaxy that are present in the solar neighborhood and are discussed by Haywood (2008).

We see in Figure 4b that there are also moderate eccentricity stars with positive  $dL$  and so mean radii exterior to their initial radius. This population of stars forms a diffuse extended stellar disk possibly similar to those sometimes seen in the outskirts of other galaxies (Bland-Hawthorn et al. 2005). Because of the large wide distribution of  $dL$  and  $e$  at later times in the outer disk (Figure 4b) the outer disk would have a reduced metallicity gradient but large metallicity scatter compared to the inner disk. Perturbations from satellites could account for the flattening of the metallicity gradient in the outskirts of other galaxies (Vlajic et al. 2009).

While we have considered only one satellite here, Kazantzidis et al. (2008) suggest that a subhalo of this size can be expected to interact with a Milky Way sized galaxy

approximately every Gyr. A galaxy of this size is suspected to have left behind  $\omega$  Cen and the  $\omega$  Cen moving group (Bekki & Freeman 2003; Meza et al. 2005). As the orbit chosen here was short, significant disk heating occurred in a short timescale ( $\sim 2.5$  Gyrs). Future studies could consider heating and mixing by more than one satellite (or halo sub-structure), those that merge and those drawn from a distribution consistent with hierarchical galaxy formation models.

In Figure 5 we show the distribution of angular momentum change versus inclination and the eccentricity versus inclination change, for stars with different initial radial bins. The inclination for each star is estimated as  $i \approx \sqrt{v_z^2 + z^2/r^2}$ . Correlations between eccentricity and inclination (see Figure 5b) and between inclination and angular momentum change are also much reduced after a few satellite orbits. Stars moved into the inner galaxy (the left hand side of panels in Figure 5a) can also be on moderate inclination orbits. We note that there is a deficit of low eccentricity and low inclination stars that have experienced large angular momentum changes, so correlations between these quantities have not been completely erased at later times.

### 3 DISCUSSION

In this paper we have used particle integration simulations to investigate the effect on the Milky Way disk of a fairly low mass satellite in a tight orbit around the Milky Way. We find that a warp, lopsidedness and spiral structure are excited in the outer disk by a satellite in an orbit similar to that estimated by the Sgr dwarf galaxy. These structures are strong providing the mass of the satellite is  $\gtrsim 5 \times 10^9 M_\odot$ , the orbit pericenter is small,  $\lesssim 10$  kpc. Perturbations are stronger when the satellite is in an inclined rather than polar orbit. If the orbital period of the satellite is short compared to the relaxation timescale of the disk then structure is increasingly excited each orbit and the disk continuously displays structure such as lopsidedness, a warp and spiral structure. Stellar orbits can intersect implying that the stellar distribution and gas distribution in the outer Galaxy could differ following tidal perturbations by a satellite. It is interesting to consider the possibility that differences between the stellar and gas distribution might be used to differentiate between models with and without warp-mode and lopsided-mode excitation.

Perturbations in the disk are also seen in a constructed velocity distribution at a specific location in the disk. This procedure creates a simulated version of the velocity distribution in the Solar neighborhood. Strong low velocity streams are present within 40km/s of the local standard of rest. Smaller streams at higher velocities can also be present, mostly at positive  $v$ , representing stars that come into the solar neighborhood from the outer galaxy. We infer that moderate velocity streams in the solar neighborhood velocity distribution could be caused by strong recent tidal perturbations in the outer Galaxy.

We find that correlations between eccentricity, inclination and angular momentum change are reduced after a few pericenter satellite passages. The eccentricity and angular momentum distribution is broad for stars born near the satellite pericenter radius, and includes low eccentricity

stars. Correlations between inclination and eccentricity are reduced after a few satellite orbits. Disk stars born in the outer galaxy can come into the inner galaxy. Some of them can be put in low eccentricity orbits at radii distant from their birth places. We infer that radial mixing and migration can be induced by satellite or subhalo perturbations in the outer disk. Such a scenario may account for the lack of strong correlation between metallicity and space velocities and moderate metallicity stars at positive  $v$  seen in the Solar neighborhood. Such a scenario may also account for flattening of the metallicity gradient in the outskirts of other galaxies (Vlajic et al. 2009).

As the simulations here integrated test particle trajectories in an isothermal gravitational potential they only poorly approximate the dynamics of the Galactic disk. The simulations here could be redone with N-body simulations and more realistic galactic mass models. Simulations which include a self-gravitating disk can investigate the excitation of global modes (e.g., Jog & Combes 2008) in context with disk heating, radial mixing and the structure of the stellar velocity distribution. The satellite orbit chosen for this study is extreme in that the pericenter distance from the Galactic center is small and the orbital period short (as is true for the estimated orbit of Sgr dwarf galaxy and that estimated for  $\omega$  Cen's progenitor; Bekki & Freeman 2003). We did not allow the satellite orbit to decay via dynamical friction, be tidally stripped or merge with the Milky Way. As the satellite spirals inwards due to dynamical friction its mass would be reduced as it is tidally stripped by the Milky Way (e.g., Zhao 2004). However it may continue to perturb the Galaxy disk as each pericenter passage brings it increasingly inward. A satellite with a higher central concentration would not be tidally disrupted until the satellite reaches a smaller galactocentric radius and so could perturb the disk over a larger range of radius than a diffuse object that is disrupted in the outer halo. A more realistic N-body based simulation that can exhibit variations in the Galactic potential and satellite orbit would probably show increased heating and migration but weaker correlations between disk stellar eccentricity, inclination and distance from birth location than the simulations explored here. Future studies could consider more realistic satellite orbits, satellites that merge with the Galaxy and more than one satellite.

We have demonstrated that radial mixing can be caused by tidal perturbations from satellite galaxies but much work remains to quantify the extent of the mixing and determine how it depends on satellite mass and orbit. Future work could compare the importance of mixing caused by satellites and that caused by transient spiral structure. If mixing associated with tidal perturbations from satellite galaxies dominates and is required to account for metallicity and velocity distributions in some regions of the Milky Way disk then one might place statistical constraints on the number, mass and orbits of objects that have perturbed and merged with the Milky Way from the observed distributions. While we have seen correlations between eccentricity, inclination and angular momentum change reduced after a few satellite pericenter passages, weak correlations between these quantities do persist. Future studies should continue to search for correlations in these quantities to probe both merger remnant related and tidally induced structure models.

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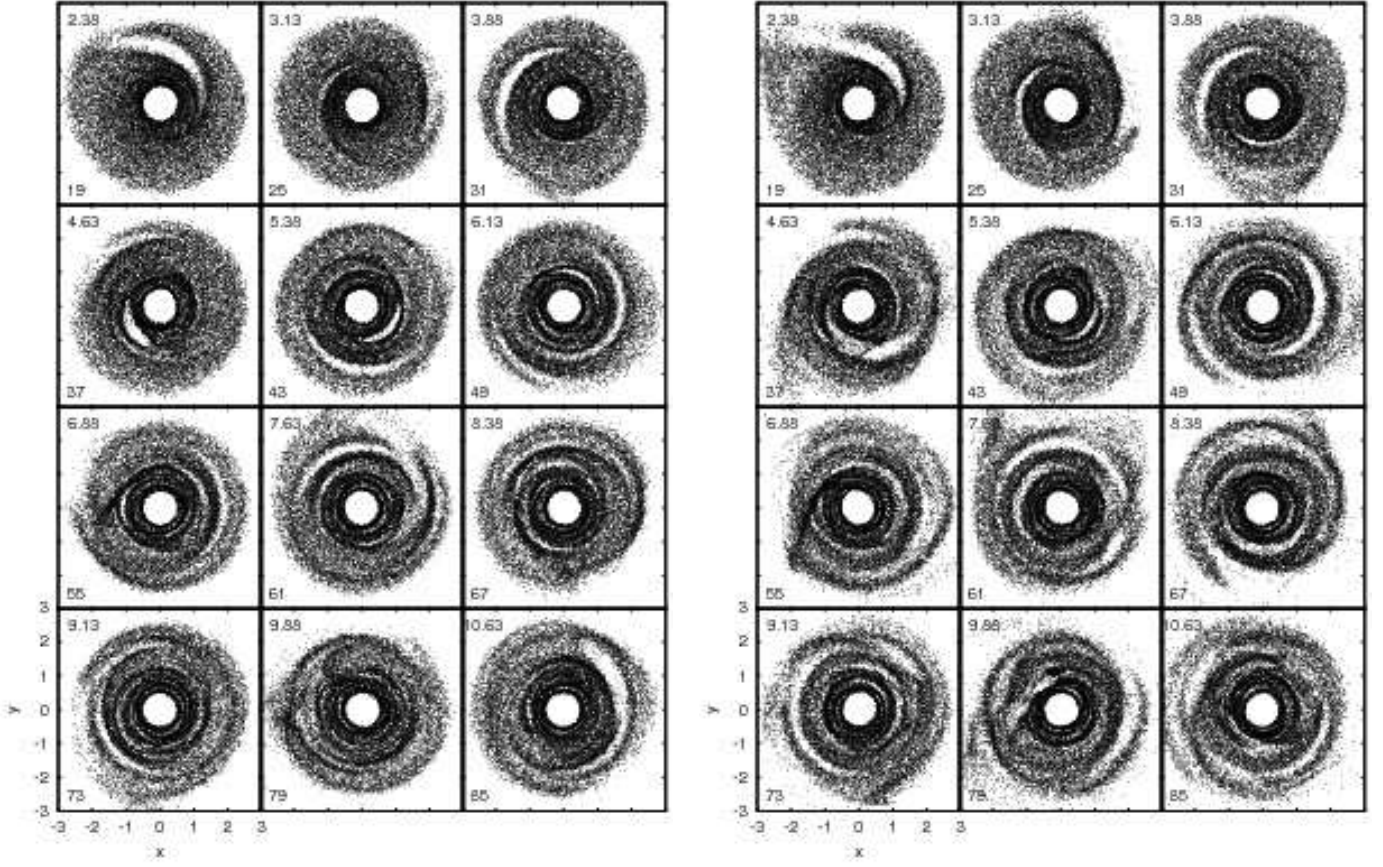
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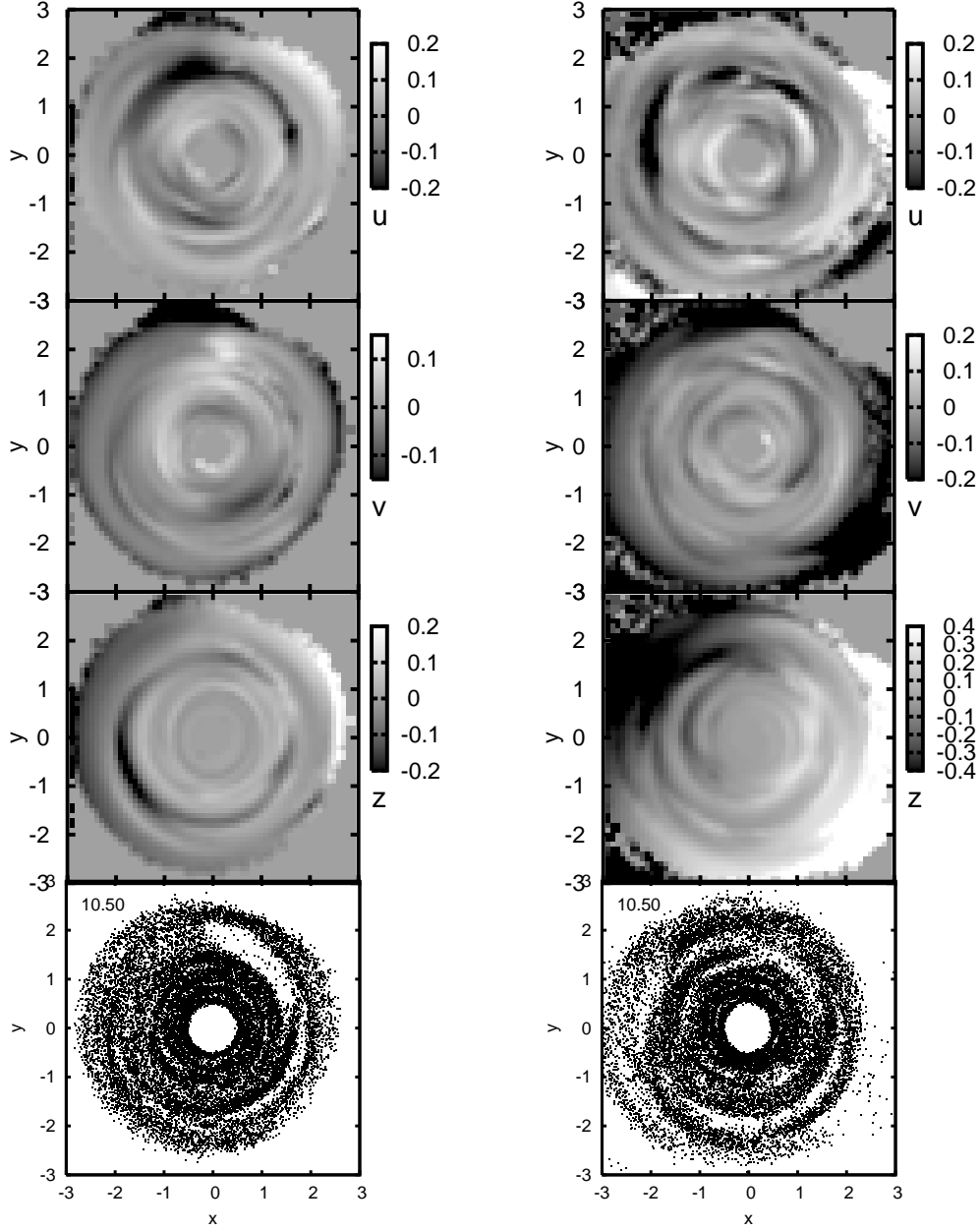
**Table 1.** Test Particle Simulations

Parameter	Value
$R_{apo}$	$6.0R_0$
$R_{peri}$	$1.3R_0$
$P_R$	$2.8 P_0$
$M_p$	$0.06 M_0$
$a$	$0.1 R_0$
$q$	$0.95$

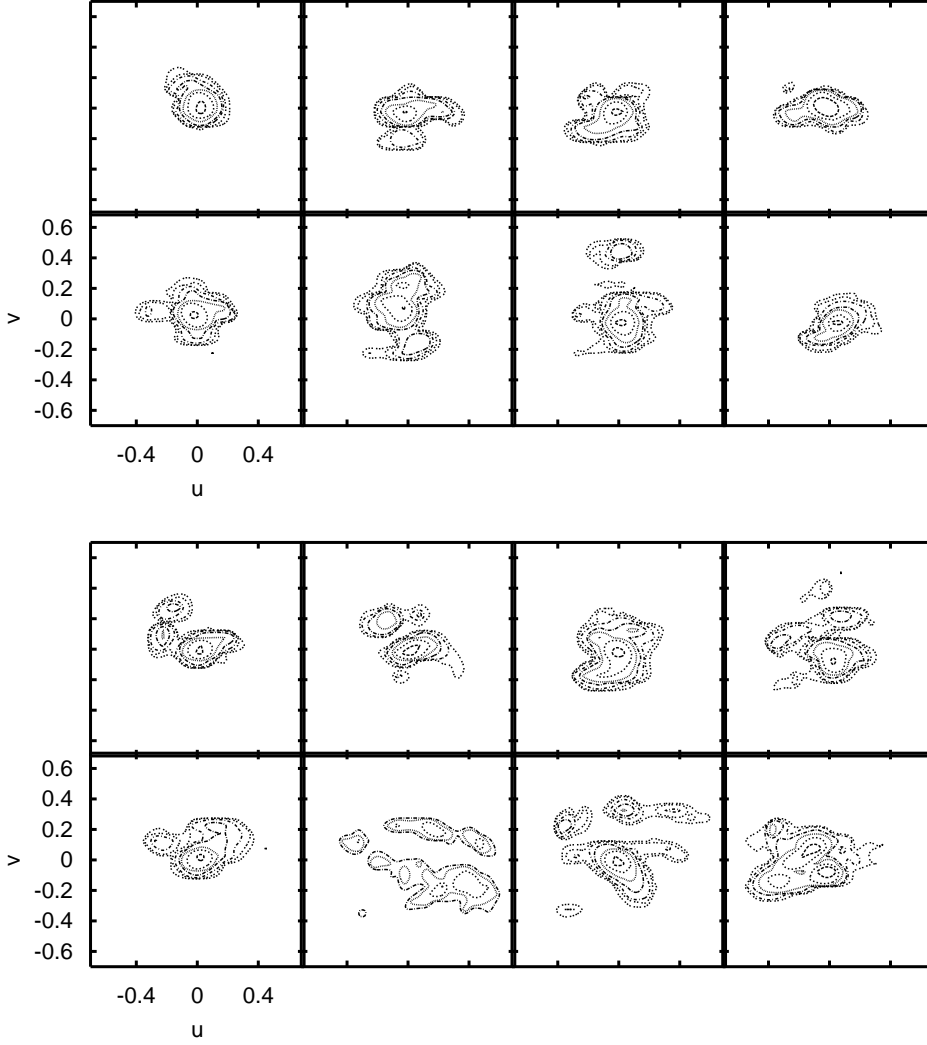
$R_{apo}$  and  $R_{peri}$  are the approximate galactocentric radii of apocenter pericenter in units of  $R_0$ . These are not exact as the halo is mildly oblate.  $M_p$  is the mass of the perturber in units of  $M_0$  which is  $\sim 10^{11} M_\odot$ .  $P_R$  is the period of radial oscillations of the satellite's orbit in units of that of the orbital period of Sun around the Galaxy. Initial disk particles are chosen between  $0.5$  and  $2.5 R_0$ . The parameter  $a$  is the softening length of the satellite and the core radius of the rotation curve. The parameter  $q$  allows the halo to be mildly oblate. Simulation A1 has satellite in a polar orbit. Simulation A2 has satellite in a prograde orbit with spin inclination  $30^\circ$  from the Galactic pole. The simulations begin with satellite at apocenter.



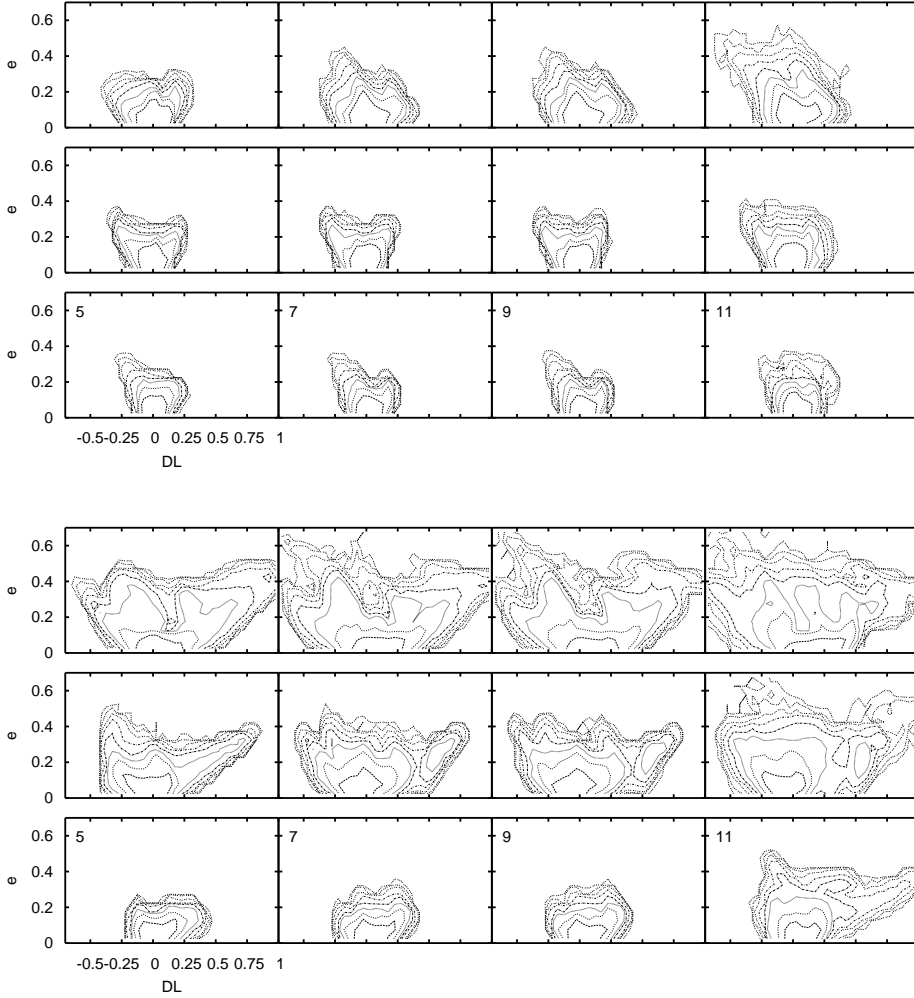
**Figure 1.** a) Structure in the plane of the galaxy for the A1 test particle simulation. Spiral structure and lopsidedness in the disk has been excited by a  $6 \times 10^9 M_\odot$  satellite galaxy in an polar orbit approximating that of the Sgr dwarf galaxy. The simulation has parameters listed in Table 1. The image is oriented so that galactic rotation is clockwise. Numbers on the upper left in each panel show time since simulation start in units of the rotation period at the Sun. Number on the lower left in each panel show the output number as positions were output every 1/8 period. Pericenters for the satellite occur at output stages 12, 33, 54 and 75. The outer disk exhibits spiral structure, a warp and is lopsided. These structures are caused by perturbations from the satellite. b) same as a) except for simulation A2 with satellite on an inclined prograde rather than polar orbit. Perturbations on the disk are stronger for this simulation.



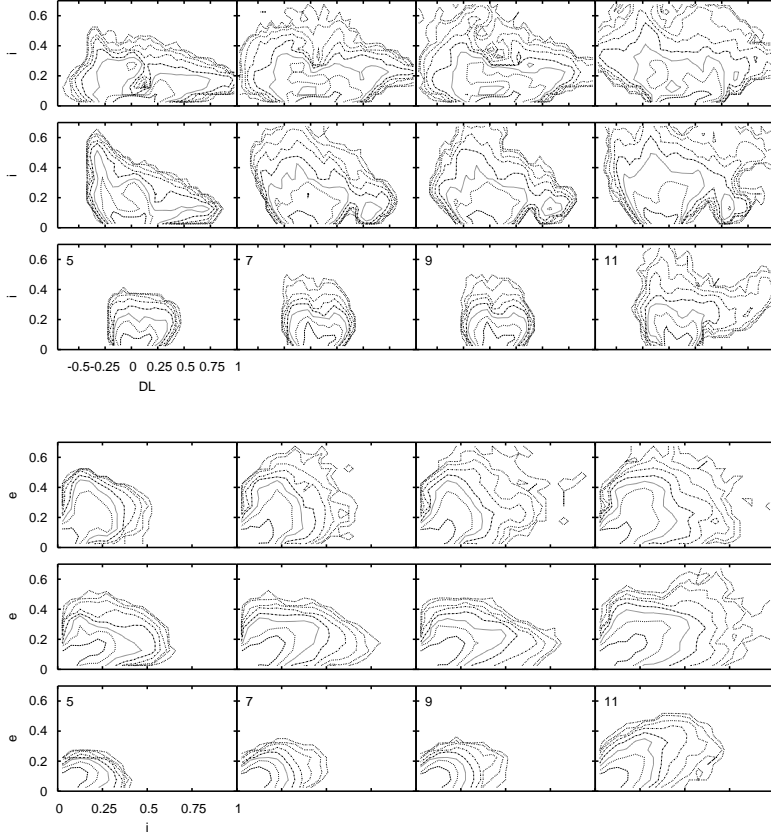
**Figure 2.** From top to bottom are shown the mean radial velocity,  $u$  (with positive  $u$  away from the Galactic center), the mean tangential velocity subtracted by the circular velocity,  $v$ , the mean height above or below the Galactic plane,  $z$ , and the disk particles projected into the plane of the galaxy. These distributions are shown when the satellite is has just passed its fourth pericenter, or at 10.5 orbital periods ( $P_0$ ) after start of simulation. The disk lopsidedness and warp have been induced by the satellite. a) (on left) For Simulation A1 with satellite on a polar orbit. b) (on right) For Simulation A2 with satellite on an inclined orbit. The velocity scale is in units of the circular velocity at  $R_0$ . The  $z$  scale is in units of  $R_0$ .



**Figure 3.** The velocity distribution in a particular region of the disk (like the solar neighborhood). a) For simulation A1. Velocity distributions are shown for stars within  $0.05 R_0$  of the position of the Sun, at (0,1) in Figure 1. The first panel (on top left) is 7.5 orbital periods after the beginning of the simulation. Each panel is separated in time by a half orbital period. Contours are logarithmically spaced with the lowest contour at 1 particle per  $0.05 \times 0.05$  square velocity bin. There are 2 contours within each factor of 10. 10 million particles were integrated to construct the velocity distribution in the small volume near the Sun. We find that clumps in the solar neighborhood velocity distribution can be induced by tidal effects associated with perturbations from a moderate mass (here  $6 \times 10^9 M_\odot$ ) satellite in a tight eccentric orbit around the Galaxy. Higher velocity streams are found at positive  $v$  and correspond to stars coming into the solar neighborhood from the outer galaxy. As the satellite is not allowed to decay, disrupt or merge, the Milky Way disk is repeatedly perturbed. The disk will not relax to a smooth distribution until the perturbations cease. b) For simulation A2. The satellite in an inclined orbit causes higher velocity streams than when the satellite orbit is polar as for simulation A1.



**Figure 4.** Shown is eccentricity versus angular momentum change distribution for stars with different initial radii (top to bottom) and at different times (left to right). From left to right we show the distribution at times separated by 2 orbital periods at  $R_0$ . Times are given on the upper left of the lower set of panels. The leftmost panels show the distribution when the satellite is at the first apocenter (after one pericenter passage) and the rightmost panels when it is at its fourth apocenter. From top to bottom we show the distribution for stars with different initial radii. The top panels show stars with initial radii in the range 1.3–1.5, the middle panels with initial radii 1.0–1.3 and the bottom panels with radii between 0.8 and 1.0. Contours are separated by a factor of  $\sqrt{10}$ . Correlations between eccentricity and angular momentum change are reduced after a few pericenter passages. There is a population of low eccentricity stars with different final angular momentum. These correspond to stars in nearly circular orbits that have been moved radially from the radii of their birth. The distribution is wide for stars with initial radii near the pericenter distance of the satellite orbit. a) For simulation A1 with satellite on a polar orbit. a) For simulation A2 with satellite on an inclined orbit.



**Figure 5.** a) Inclination versus angular momentum distribution for simulation A2. This is displayed similarly to Figure 4. b) Inclination versus eccentricity distribution for simulation A2. We find that correlations between eccentricity and inclination are also reduced after a few pericenter passages.